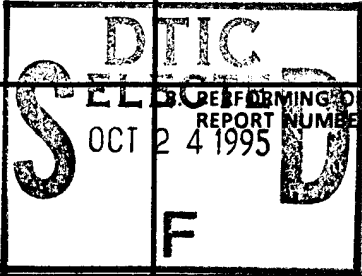# REPORT DOCUMENTATION PAGE

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12a. DISTRIBUTION/AVAILABILITY STATEMENT

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12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Finite element analysis of static and dynamic fracture of brittle microcracking solids was performed. The continuum constitutive modeling for rate-dependent fracture of brittle microcracking solids is discussed. The rate-type constitutive equation that is proposed takes into account the rate effect on microcracking and plastic deformation. In order to test the validity of the proposed modeling, numerical studies were conducted on a bar under uniaxial tension, a beam under pure bending, and on the phenomenon of microcracking around the tip of a macrocrack under mode-I loading. Finite element analysis of stationary and rapidly-propagating macrocracks under dynamic loading. The microcrack toughening effect is discussed, along with the influence on it of the size of the microcracked process zone and the various parameters in the microcrack density evolution equation, through the observation of the behavior of the general crack-tip energy-release parameter, the T integral. Some important aspects associated with the transformation induced plasticity in $Al_2O_2ZrO_2$ are analyzed using a computer simulation based on Fininte Element Method (FEM).

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7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

> 1. Finite Element Analysis of Static and Dynamic Fracture of Brittle Microcracking Solids: Part 1. Int. J. Plasticity, Vol. 6, pp.169-188, 1990. (with Y. Toi)
> 2. Finite Element Analysis of Static and Dynamic Fracture of Brittle Microcracking Solids: Part 2. Int. J. Plasticity, Vol. 6, pp. 263-280, 1990.(with Y. Toi)
> 3. Finite Element Analysis of Static and Dynamic Fracture of Brittle Microcracking Solids: Part 3. Int. J. Plasticity, (In Press) 1990.(with Y. Toi)
> 4. Computer Simulation of Transformation Induced Plasticity using Finite Element Method. Acta Mechanica (to appear) 1990. (with N. Ramakrishnan)
> 5. Fracture Toughness Enhancement Mechanisms in Ceramic Composites. (to appear) 1990. (H. Okada, Ph.D. Thesis)

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

> 1. H. Okada, Ph.D. thesis completed July 1990.
> 2. Dr. N. Ramakrishnan, Post-Doctoral Fellow.
> 3. D. Scott Pipkins, Ph.D. student.

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BRIEF OUTLINE OF RESEARCH FINDINGS

Finite Element Analysis of Static and Dynamic Fracture of Brittle Microcracking Solids: Part 1:

The continuum constitutive modeling for rate-dependent fracture of brittle microcracking solids is discussed. The rate-type constitutive equation that is proposed takes into account the rate effect on microcracking and plastic deformation. In order to best the validity of the proposed modeling, numerical studies are conducted on a bar under uniaxial tension, a beam under pure bending, and on the phenomenon of microcracking around the tip of a macrocrack under mode-I loading.

Finite Element Analysis of Static and Dynamic Fracture of Brittle Microcracking Solids: Part 2:

The continuum constitutive modeling for rate-dependent fracture of brittle microcracking solids, which was described in part 1 of this paper, is applied to the finite element analysis of stationary and nonstationary macrocracks in a single-edge-notched three-point bend specimen under a

static loading. The microcrack damage zones near the macro-crack-tip can be classified as being "large-scale". The microcrack toughening effect in stationary cracks is observed through the behavior of the crack tip energy flux parameter, the T^* integral. The numerical results of the nonstationary crack analysis are compared with the available experimental results for a silicon carbide specimen.

Finite Element Analysis of Static and Dynamic Fracture of Brittle Microcracking Solids: Part 3:

The continuum constitutive modeling for rate-dependent fracture of brittle microcracking solids, which was described in part 1 of this paper, is applied to the finite element analysis of stationary and rapidly-propagating macrocracks under dynamic loading. The microcrack toughening effect is discussed, along with the influence on it of the size of the microcracked process zone and the various parameters in the microcrack density evolution equation, through the observation of the behavior of the general crack-tip energy-release parameter, the T^* integral.

Computer Simulation of Transformation Induced Plasticity using Finite Element Method:

Some important aspects associated with the transformation induced plasticity in Al_2O_3-ZrO_2 are analyzed using a computer simulation based on Finite Element Method (FEM). These aspects include: (i) an estimation of the residual stress in the second phase, arising during post fabrication cooling, which affects the critical stress for transformation, (ii) the constitutive behavior of the material during the dilatational transformation of ZrO_2 and (iii) the crack deflection due to the transformation. This simulation study was conducted for angular as well as spherical shapes of second phase particles and also for varying volume fractions of the second phase, using a master finite element mesh. Apart from this numerical experiment, analytical expressions were derived for the residual stress and the constitutive behavior, assuming a spherical shape for the second phase particles. The analysis of the constitutive behavior mainly consists of an estimation of the composite modulus and of the irreversible strain due to the transformation. The comparison of the analytical solutions with the results obtained through the simulation shows a very good agreement. Using the simulation of crack deflection, the increase in crack surface area due to the transformation was computed, to approximately estimate the improvement in fracture toughness due to the crack deflection mechanism.

Fracture Toughness Enhancement Mechanisms in Ceramic Composites:

The transformation toughening and microcracking have been found to be the key phen-omena in enhancing the fracture toughness of ceramic composite materials. The transformation toughening phenomenon is generally seen in ceramic materials which contain tetragonal zirconia phase (t-ZrO_2). The tetragonal zirconia particles transform to monoclinic structure under high stress. In the case of crack propagation, the transformation results in a significant amount of irreversible strain around the crack tip, thereby enhancing the fracture toughness. On the other hand, the microcrack toughening enhances the fracture toughness of the ceramic materials by reducing the stress intensity at the crack tip, and this phenomenon is associated with the reduction of the elastic moduli of microcracked material. Also, coupled microcracking and transformation-toughening phenomenon has also been reported, that is, the phase transformation of zirconia particles induces microcracking in the matrix material, thereby resulting in a larger amount of irreversible strain than that of the transformation alone. These deformation mechanisms are not additive and the coupling effect is not well understood.

In this study, a nonlinear constitutive model for the transformation induced plasticity is presented. This nonlinear constitutive model is implemented in a nonlinear finite element method and applied to crack problems. Stationary crack and steady state crack propagation problems are analyzed to estimate the fracture toughness enhancement due to the transforamtion effect. The constitutive equations derived in this investigation are in the rate (incremental) form, and are ideally suited for implementing in the existing nonlinear finite element codes. It is assumed that the transformation plasticity is dilatationally nonlinear and distortionally linear, and exhibits dilatational strain softening. Dilatational irreversible strain, for the coupled microcracking-transformation case, as a function of volume fraction of transformed zirconia is also derived. With this investigation, a better insight into the mechanisms of fracture toughness enhancement in certain ceramic materials is found.

PROGRESS REPORT

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2) **PERIOD COVERED BT REPORT:** 1 January 1989 - 30 June 1989

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5) **NAME OF INSTITUTION:** Georgia Institute of Technology

6) **AUTHORS OF REPORT:** S.N. Atluri

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   1. Finite Element Analysis of Static and Dynamic Fracture of Brittle Micro-cracking Solids: Part 1: Formulation & Numerical Examples; *International Journal of Plasticity* (accepted for publication); (By Y.Toi and S.N. Atluri)

   2. Finite Element Analysis of Dynamic Fracture of Brittle Microcracking Solids in *Proc ASME Pressure Vessels & Piping Conference,* Honolulu, 23 July - 27 July 1989; (Y. Toi & S.N. Atluri)

8) **SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:**

   Mr. F. Mello; PhD Student; Dr. Y. Toi, Post-Doc; Mr. S. Pipkins, PhD student

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BRIEF OUTLINE OF RESEARCH FINDINGS

1)   **Contact with Army Laboratory Personnell:**

Dr. R. Ahmad of ARO, and Dr. Tony Chou of Army Materials
Technology Labs, visited Georgia Tech in Febuary 1989. A
presentation was made by S.N. Atluri.

2)   **Brief outline of Research:**

The continuum constitutive modeling for rate dependent fracture of
brittle microcracking solids has been pursued. A rate-type constittutive
equation that takes into acccount the rate effect on microcracking has
been proposed. Its computational implementation via a finite element
method has been undertaken. A computationl method for the analysis
of stationary as well as dynamically propagating macrocracks has been
formulated. The effect on microcracking surrounding a macrocrack is
being studied through as analysis of the behavior of the general crack-
tip energy-release-rate parameter, the T^* integral.